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ADAPTIVE ANTENNA ARRAY SYSTEM AND

WEIGHTING COEFFICIENT COMPUTATION CONTROL METHOD

BACKGROUND OF THE INVENTION

5   Field of the Invention

The present invention relates to an adaptive antenna array system and a method of calculating and controlling weighting coefficient.

Priority is claimed on Japanese Patent Application No. 2003-95364, filed March 31, 2003, the content of which is incorporated herein by reference.

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Description of Related Art

In conventional adaptive antenna array systems, an antenna array is provided that is composed of a plurality of antenna elements, and the received signal of each antenna element is synthesized and output after weighting the signal using a weighting

15   coefficient for controlling the directivity of the antenna array.   In addition, a known example of a method of calculating the weighting coefficient involves the use of an adaptive algorithm based on the minimum mean square error (MMSE) to calculate the weighting coefficient using adaptive control so as to minimize the square error between the received signal of each antenna element and a reference signal (refer to, for example,

20   Nobuyoshi Kikuma, ed., "Adaptive Signal Processing by Antenna arrays", Science Press, Inc., Nov. 1998, p. 13-66).   Examples of the aforementioned MMSE-based adaptive algorithm include Least Means Square (LMS) and Recursive Least-Squares (RLS).

In addition, a system has also been studied that reduces the power consumption of the arithmetic processing device (e.g., digital signal processor (DSP)) by reducing the

25   number of calculations for updating the aforementioned weighting coefficient.   In this

type of system, as is shown, for example, in Japanese Unexamined Patent Application, First Publication No. 2002-77012, by evaluating the propagation path characteristics of a received signal, and controlling the number of updates of the aforementioned weighting coefficient corresponding to the results of this evaluation, the number of calculations for

5 updating the weighting coefficient is known to be reduced. An example of a parameter used to represent propagation path characteristics is the phasing speed of a mobile terminal device. If the phasing speed is slower than a predetermined value, there is judged to be little fluctuation in the weighting coefficient itself, and the weighting coefficient calculated with the previous frame is continued to be used, thereby reducing

10 the number of updates of the weighting coefficient. For example, the number of updates is taken at a ratio of one frame for each of a predetermined number of frames.

In addition, updating processing of the weighting coefficient may be made to not be performed until the error of the weighting coefficient increases to the extent that a cyclic redundancy check (CRC) error or other reception error occurs in the received

15 signal.

However, the aforementioned prior art has the problems indicated below.

In the case of a system that reduces the number of updates of the weighting coefficient based on the phasing speed of a mobile terminal device, since the judgment as to whether or not the number of updates of the weighting coefficient can be reduced is

20 dependent upon empirically obtained conditions, the number of updates is not always reduced corresponding to the fluctuation in the weighting coefficient, thereby resulting in the risk of deterioration of reception quality.

In addition, in the case of a system that updates the weighting coefficient after a reception error is generated, there is the risk of having a serious detrimental effect on

25 reception quality, thereby making this undesirable.

In order to accurately make the weighting coefficient follow fluctuations in the propagation path characteristics of a received signal, it is not desirable to reduce the number of updates of the weighting coefficient. On the other hand, a large number of calculations increases the current consumption of the mobile terminal, thereby having the

5   detrimental effects of increased battery size and shortened battery life.

On the basis of such reasons, there is a need to obtain a suitable weighting coefficient while also reducing the number of calculations required.

In consideration of such circumstances, the object of the present invention is to provide an adaptive antenna array system and weighting coefficient calculation and

10   control method capable of reducing current consumption by reducing the number of calculations required to obtain a suitable weighting coefficient.

SUMMARY OF THE INVENTION

The first aspect of the present invention is an adaptive antenna array system

15   having an antenna array comprising a plurality of antenna elements, the antenna array synthesizing received signals received by each of the antenna elements by weighting them according to a weighting coefficient and outputting a synthesized signal, a weighting coefficient calculation unit for calculating the weighting coefficient of received signals by adaptive control, an evaluation unit for evaluating the convergence

20   status of adaptive control by the weighting coefficient calculation unit, and a control unit for controlling the operation of adaptive control by the weighting coefficient calculation unit corresponding to the results of evaluation of convergence status by the evaluation unit.

In the above adaptive antenna array system, the weighting coefficient calculation

25   unit may calculate the weighting coefficient by adaptive control using an adaptive

algorithm based on the minimum mean square error method so as to minimize the moving average square error between a reference signal and an output signal, and the evaluation unit may judge that adaptive control by the weighting coefficient calculation unit has converged in the case the moving average square error is continuously below a predetermined value for a predetermined number of times.

In the above adaptive antenna array system, the weighting coefficient calculation unit may calculate the weighting coefficient by adaptive control using an adaptive algorithm based on the minimum mean square error method so as to minimize the moving average square error between a reference signal and an output signal, and the evaluation unit may judge that adaptive control by the weighting coefficient calculation unit has converged in the case the rate of change of the moving average square error has fallen below a predetermined value.

In the above adaptive antenna array system, the control unit may stop the operation of adaptive control by the weighting coefficient calculation unit, when the control unit judges by the evaluation unit that adaptive control by the weighting coefficient calculation unit has converged.

In the above adaptive antenna array system, the control unit may intermittently activate adaptive control by the weighting coefficient calculation unit, when the control unit judges by the evaluation unit that adaptive control by the weighting coefficient calculation unit has converged.

In the above adaptive antenna array system, the control unit may intermittently activate adaptive control by the weighting coefficient calculation unit at a specific interval.

In the above adaptive antenna array system, the control unit may return adaptive control by the weighting coefficient calculation unit to the steady state when conditions

for judging convergence of adaptive control by the evaluation unit are no longer satisfied in the case adaptive control by the weighting coefficient calculation unit is being activated intermittently.

In the above adaptive antenna array system, the control unit may adaptively control the interval at which adaptive control by the weighting coefficient calculation unit is activated intermittently.

The second aspect of the present invention is a weighting coefficient calculation and control method in an adaptive antenna array system which includes an antenna array composed of a plurality of antenna elements, and synthesizes received signals received with the antenna elements by weighting the signals according to a weighting coefficient and outputs a synthesized signal, the method having a weighting coefficient calculation step for calculating the weighting coefficient of the received signals by adaptive control, an evaluation step for evaluating the convergence status of adaptive control by the weighting coefficient calculation step, and a control step for controlling operation of adaptive control by the weighting coefficient calculation step corresponding to the results of the evaluation of convergence status by the evaluation step.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram showing the configuration of an adaptive antenna array system according to an embodiment of the present invention.

FIG. 2 is a drawing showing a portion of the configuration of a frame used when radio signals are received by the system of FIG. 1.

FIG. 3 is a drawing for explaining the method for evaluating convergence status of adaptive control in the present embodiment.

FIG. 4 is a drawing for explaining one method for controlling the operation of

adaptive control in the present embodiment.

FIG. 5 is a first drawing showing simulation results obtained by one method for controlling the operation of adaptive control in the present embodiment.

FIG. 6 is a second drawing showing simulation results obtained by one method

5   for controlling the operation of adaptive control in the present embodiment.

DETAILED DESCRIPTION OF THE INVENTION

The following provides an explanation of an embodiment of the present invention with reference to the drawings.   Furthermore, in the present embodiment, the

10   example of Code Division Multiple Access (CDMA) system referred to as "cdma2000 lxEV-DO" is used to explain the wireless communication system.

FIG. 1 is a block diagram showing the configuration of an adaptive antenna array system according to an embodiment of the present invention.   The adaptive antenna array system shown in FIG. 1 has, for example, a mobile station (e.g., cellular

15   phone) provided in the "cdma2000 lxEV-DO" type of wireless communication system, and receives radio signals transmitted from a wireless base station using a plurality of antenna arrays consisting of ANT1 through ANT4 (four are shown in FIG. 1), followed by synthesizing received signals by weighting with a weighting coefficient.

FIG. 2 shows a portion of the configuration of a frame used when transferring

20   radio signals from a wireless base station to a mobile station in the "cdma2000 lxEV-DO" wireless communication system.   The frame shown in FIG. 2 is used when radio signals are received by the system shown in FIG. 1.   FIG. 2 shows the configuration of a time slot, a plurality of which are multiplexed based on time division within the frame.   In this FIG. 2, the pilot signal is a known signal, and is composed of

25   96 elements (96 chips) of a diffusion signal (PN code) in the CDMA system.   The pilot

signal is used to calculate the weighting coefficient by adaptive control. For example,

pilot signal 101 is used to calculate the weighting coefficient Wk for received signals

over the interval from the following MAC signal to the next pilot signal 102.

In FIG. 1, the adaptive antenna array system is provided with an antenna array

5 composed of four antenna elements ANT1 through ANT4, a wireless unit 2, multipliers 4,

an adder 8, a weight calculation unit 10, a reference signal storage unit 12, a convergence

status evaluation unit 14 and a weight calculation control unit 16.

Wireless unit 2 amplifies the radio signals from antenna elements ANT1 through

ANT4, and after converting them to base band signals, outputs received signals X_1

10 through X_4 following conversion to digital signals by an analog to digital converter (A/D

converter). These signals X_1 through X_4 correspond to antenna elements ANT1 through

ANT4, respectively.

Multipliers 4 are provided corresponding to each antenna element ANT1

through ANT4. The received signal corresponding to each antenna element is input to

15 each multiplier 4 from wireless unit 2. In addition, a weighting coefficient

corresponding to each antenna element is input to each multiplier 4 from weight

calculation unit 10.

Multipliers 4 carry out weighting by multiplying the input received signals by a

weighting coefficient from weight calculation unit 10. The weighted received signals

20 are then input to adder 8. Adder 8 synthesizes a signal by adding the weighted received

signals input from each multiplier 4 to generate and output an output signal Y. In

addition, this output signal Y is input to weight calculation unit 10.

Weight calculation unit 10 (weighting coefficient calculation unit) calculates a

weighting coefficients W_1 through W_4 for controlling the directivity of the antenna array

25 composed of antenna elements ANT1 through ANT4 using an MMSE-based adaptive

algorithm.   The least mean square (LMS) method or recursive least-squares (RLS) method can be used for this adaptive algorithm.

A reference signal r from reference signal storage unit 12, received signals X_1 through X_4 and output signal Y from wireless unit 2, and a control command from weight

5   calculation control unit 16 are input to weight calculation unit 10.   Reference signal storage unit 12 has reference signal r corresponding to a known pilot signal shown in the aforementioned FIG. 2 pre-stored in memory.

Weight calculation unit 10 calculates weighting coefficients W_1 through W_4 by adaptive control using input reference signal r, received signals X_1 through X_4 and output

10   signal Y so as to minimize the moving average square error E between reference signal r and output signal Y.   Computational processing of these weighting coefficients is carried out on a pilot signal composed of 96 chips.   Namely, each time a pilot signal is received, the calculated weighting coefficients W_1 through W_4 are respectively input to the corresponding multipliers to update the weighting coefficients.

15   Weight calculation unit 10 performs arithmetic processing of adaptive control in chip units in order starting with the first chip in the pilot signal during a single round of weighting coefficient updating processing.   In the case a control command has been received from weight calculation control unit 16, arithmetic processing of adaptive control is performed in accordance with that control command.

20   In addition, weight calculation unit 10 outputs the aforementioned moving average square error E to convergence status evaluation unit 14 for each arithmetic processing of adaptive control of the pilot signal in chip units.   Moving average square error E is defined by equations 1 and 2.

(Equation 1)

$$e(t) = \left| r(t) - W_k^H(t)X(t) \right|^2$$

(Equation 2)

$$E(m) = \frac{1}{L} \sum_{n=m-L+1}^{m} e(t_n)$$

In these equations, t represents the time in chip units from the first chip to the

5   96th chip, r(t) represents the reference signal at time t, $W_k(t)$ represents weighting

coefficient vectors $[W(t)_1\text{-}W(t)_4]$ at time t, X(t) represents the received signal vectors

$[X(t)_1\text{-}X(t)_4]$ at time t, e(t) represents the momentary square error at time t, E(m)

represents the moving average square error over moving average interval m, L represents

the moving average length, t_n represents the time corresponding to the nth chip (n = 1, 2,

10   3, . . . 96), and H is the notation for the complex conjugate transposition.

Convergence status evaluation unit 14 (evaluation unit) evaluates the status of

convergence of adaptive control by weight calculation unit 10 based on moving average

square error E from said weight calculation unit 10.   A detailed description of this

evaluation method is provided later.   Convergence status evaluation unit 14 outputs the

15   results of evaluation to weight calculation control unit 16.

Weight calculation control unit 16 (control unit) controls the operation of

adaptive control by weight calculation unit 10 corresponding to the evaluation results

from convergence status evaluation unit 14.   The method for controlling operation of

adaptive control is described in detail later.

20   Next, an explanation is provided of the aforementioned method used to evaluate

the convergence status of adaptive control.

In the present embodiment, the convergence status of adaptive control by weight

calculation unit 10 is evaluated based on the moving average square error E.   Although

various methods may be considered for performing this evaluation, the following

provides an explanation of the method using the following example.

First, an explanation is provided of a first evaluation method. FIG. 3 is a

drawing for explaining the first evaluation method. In this first evaluation method, as

5   shown in FIG. 3, if moving average square error E is continuously below a

predetermined threshold value Th for a predetermined number of times, adaptive control

by weight calculation unit 10 is judged to have converged. Alternatively, adaptive

control may also be judged to have converged if moving average square error E is below

predetermined threshold value Th even once. A value, for example, corresponding to

10   the lower limit value of CIR based on the dynamic range of CIR should be selected for

the value of the aforementioned threshold value Th.

Next, an explanation is provided of a second evaluation method. In this second

evaluation method, a judgment of whether or not adaptive control by weight calculation

unit 10 has converged is made on the basis of the rate of change of moving average

15   square error E. The rate of change β of moving average square error E is defined by

equation 3.

(Equation 3)

$$\beta(m) = \frac{|E(m) - E(m-1)|}{E(m)}$$

Adaptive control is judged to have converged if the rate of change β is smaller

20   than a predetermined threshold value $\beta0$.

When convergence status evaluation unit 14 has judged that adaptive control by

weight calculation unit 10 has converged, it notifies weight calculation control unit 16 to

that effect.

In the present embodiment as described above, adaptive control by weight calculation unit 10 is judged to have converged based on moving average square error E. Moving average square error is known to correlate with the degree of improvement of carrier to interference ratio (CIR). CIR serves as a representation of reception characteristics. Thus, a weighting coefficient when adaptive control has been judged to have converged is able to maintain satisfactory reception quality by using a threshold value Th or $\beta 0$ corresponding to a satisfactory CIR.

Next, an explanation is provided of the aforementioned method for controlling the operation of adaptive control. In the present embodiment, during each round of updating processing of the weighting coefficient for a single pilot by weight calculation unit 10, the operation of adaptive control by weight calculation unit 10 is controlled so as to reduce the number of calculations during subsequent weighting coefficient updating processing after adaptive control by weight calculation unit 10 has been judged to have converged by the aforementioned evaluation method. Although various methods can be considered for this method for controlling the operation of adaptive control, the following provides an explanation of examples of that method.

First, an explanation is provided of a first operation control method. In this first operation control method, operation of adaptive control is stopped once adaptive control by weight calculation unit 10 has been judged to have converged. As a result, weight calculation unit 10 no longer computes adaptive control for a chip once it has received a command to stop operation. Weight calculation unit 10 then uses the weighting coefficient at the time the operation was stopped to update the weighting coefficient. As a result, the number of calculations for updating the weighting coefficient in weight calculation unit 10 is reduced.

Next, an explanation is provided of a second operation control method. FIG. 4

is a drawing for explaining a second operation control method. In this second operation control method, as shown in FIG. 4, adaptive control is operated intermittently instead of for each chip once adaptive control by weight calculation unit 10 has been judged to have converged. As a result, weight calculation unit 10 computes adaptive control for one chip only once it has received a command to start the operation. Weight calculation unit 10 then uses the weighting coefficient obtained in the last computation of adaptive control to update the weighting coefficient. As a result, together with the number of calculations for updating the weighting coefficient in weight calculation unit 10 being reduced, adaptive control is performed at a time that is as close as possible to the received signal to which the weighting coefficient is applied, thereby improving the accuracy of the weighting coefficient.

Furthermore, the aforementioned intermittent operation method may be activated at a specific interval.

In addition, in the case adaptive control by weight calculation unit 10 is operated intermittently, the adaptive control may be returned to the steady state once the conditions for judging convergence based on the aforementioned threshold value Th or threshold value $\beta 0$ are no longer satisfied.

In addition, the operating interval may also be controlled adaptively. In one example of such a method for adaptive control of the operating interval, the moving average square error E is monitored by convergence status evaluation unit 14 once it has been judged to have converged. The operating interval may then be made to increase during the time the moving average square error E is decreasing, and may be made to decrease during the time the moving average square error E is increasing. For example, a chip (time) targeted for adaptive control is controlled according to equation 4.

(Equation 4)

$$t_{n+1} = t_n + \Delta t_{n+1}$$

In this equation, Δt_{n+1} is $\Delta t_{n+1} + 1$ when $\beta(n) < \beta 0$, and 1 when $\beta(n) \geq \beta 0$.

FIGS. 5 and 6 show the results of simulations in the case of adaptively controlling the operation interval for adaptive control according to the aforementioned

5   equation 4.   FIG. 5 shows the cumulative distribution of the number of computations for adaptive control, while FIG. 6 shows the cumulative distribution of the degree of improvement in CIR.

As shown in FIG. 5, the number of computations for adaptive control decrease corresponding to the value of threshold $\beta 0$.   In contrast, as shown in FIG. 6, the degree

10   of improvement in CIR is roughly the same even through the value of threshold $\beta 0$ changes.   In this manner, according to the present embodiment, in addition to being able to maintain reception quality, the number of calculations required until a suitable weighting coefficient is obtained can be reduced.   As a result, the amount of power consumed by the DSP and other components is reduced.

15   Furthermore, the adaptive antenna array system of the present invention can be similarly applied to a wireless base station.   In addition, it can also be applied to various wireless communication systems such as the aforementioned "cdma2000 1xEV-DO" system provided the system computes the weighting coefficients of received signals by adaptive control.

20   Although the aforementioned explanations have provided a detailed description of an embodiment of the present invention with reference to the drawings, the concrete conFIGuration is not limited to this embodiment, but rather design changes and so forth are also included within a scope that does deviate from the gist of the present invention.

As has been explained above, according to the present invention, since the

convergence status of adaptive control is evaluated during calculation of a weighting

coefficient, and the operation of said adaptive control is controlled corresponding to the

result of that evaluation, the number of calculations required to obtain a suitable

weighting coefficient can be reduced.   As a result, since the power consumed by DSP

5   and other components is reduced, a reduction in power consumption can be achieved.

While preferred embodiments of the invention have been described and

illustrated above, it should be understood that these are exemplary of the invention and

are not to be considered as limiting.   Additions, omissions, substitutions, and other

modifications can be made without departing from the spirit or scope of the present

10   invention.   Accordingly, the invention is not to be considered as being limited by the

foregoing description, and is only limited by the scope of the appended claims.